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# Present status of photovoltaic energy in Turkey and life cycle techno-economic analysis of a grid-connected photovoltaic-house

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## Abstract

The electricity consumption in Turkey increased on average 8.5% annually between 1990 and 2000, but decreased 1.2% in 2001 due to the economic crisis of 2000. The economic growth and electricity consumption are expected to continue in a similar rate of before the crisis in the coming years. Turkey is going through a change of policy in the energy sector, adopting a policy of privatisation. On the other hand, Turkey needs adaptations in the energy field for meeting the European standards as Turkey is seeking a full membership to the European Union. The alternative and renewable energy systems have been neglected so far in Turkey but must be included in the new energy programs. The renewable energy contribution in the total primary energy production is insignificant. The current installed photovoltaic capacity is in the level of a fraction of MW, which is tiny when compared to the solar energy potential in Turkey.

In this article, a photovoltaic-house, which would have photovoltaic as the main energy source, is hypothetically designed to assess the techno-economic feasibility of grid-connected photovoltaic systems in Turkey. The grid electricity is used when the photovoltaic system fails to meet the required electricity. The performance of the photovoltaic system is simulated on an hourly basis to determine the autonomy level, using one year long hourly time-series solar radiation data of Ankara obtained from the Turkish State Meteorological Service. Then, some combinations of photovoltaics and grid electricity with different buy-back ratios are analysed.


*Keywords:* Photovoltaic energy in Turkey; Grid-connected photovoltaic energy systems; Performance-cost optimisation

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## 1. Introduction

Energy has played a key role in the development of human being since the industrial revolution of the 18th century. The consumption of energy per head has dramatically increased since then as the standard of living has improved significantly. However, after the energy crisis of 1970s, until then taken as granted, it was realised that the fossil energy reserves were limited on earth. The fossil energy resources are sufficient only for a limited number of years. Even though the coal reserve is enough for the next two centuries, its usage must be restricted to a minimum for its demolishing ecological effects. The environmental aspects of energy systems have gained priority as the environmental awareness of human being increased. As a result, the renewable energy systems have been included in the energy research programs and in the energy policies of the governments. The cleanness of an energy source became an important parameter in energy programs especially in developed countries and the contribution of renewable energy systems such as solar, wind and geothermal relatively increased. The developing countries are also including more of renewable energy systems in their energy programs for a sustainable economic growth.

Turkey is going through a change of policy in the energy sector, adopting a policy of privatisation of some of the state-owned energy companies. On the other hand, Turkey needs adaptations in the energy field for meeting the European standards as Turkey is seeking a full membership to the European Union (EU). Due to the limited primary energy resources, the rate of primary energy production to consumption is noticeably decreasing in Turkey. The current rate of Turkey's primary energy production to consumption of 35%

is expected to decrease to 33% in 2005, 30% in 2010 and 26% in 2020 [1]. This requires more energy to be imported in the form of either electricity or primary energy source, such as oil or natural gas in the near future. In order to limit the energy to be imported, the contribution of renewable energy resources in the total electric generating capacity has to be increased. Especially wind and solar may compensate for the declining rate of primary energy resources. The total 27.260 MWe of installed electricity capacity in Turkey (as of 2001) was mainly of hydroelectric power stations (41%) and conventional thermal power plants (58.9%). The renewable energy contribution to this installed electricity capacity was negligible with a total installed capacity of 0.04 MWe [2]. Current 4000 MWe gas-fuelled generation capacity of Turkey will approximately reach 18.500 MWe by the year 2010, with the new power plants that are either under construction or in the planning stages. This however will increase the dependency more and more on the imported natural gas since only a tiny fraction of the natural gas consumed in Turkey is met by indigenous sources. The electricity consumption in Turkey increased on average 8.5% annually between 1990 and 2000, but decreased 1.2% in 2001 due to the economic crisis of 2000 [2]. However, the economic growth and electricity consumption are expected to continue in the same level as experienced between 1990 and 2000 in the coming years since the crisis seems to be subdued. Therefore, the electric generating capacity has to increase rapidly, as much as twice in the next 10 years. The expected electric power capacity development in Turkey is summarised in Table 1 for 2010 and 2020.

The total installed photovoltaic power capacity in Turkey is estimated around 300 kW, which should be increased in a near future, together with other renewable energy systems. The known applications of photovoltaics are summarised in Table 2, which is 271.52 kW. The potential of Turkey as a photovoltaic market is very large, since the country abounds in solar radiation and large areas of available land for solar farms. There are more than 30.000 small residential areas where solar powered electricity would likely be more economical than grid supply as well as the holiday villages at the long coastal areas [3]. The current installed photovoltaic power is relatively small considering the high solar energy resource in Turkey as summarised in Table 3 regionally.

Table 1
Expected electric power capacity development in Turkey

| Fuel type | 2010 | | 2020 | |
|---|---|---|---|---|
| | Installed capacity (MWe) | Generation (GWh) | Installed capacity (MWe) | Generation (GWh) |
| Coal | 16,106 | 104,035 | 26,906 | 174,235 |
| Natural gas | 18,856 | 125,548 | 34,256 | 225,648 |
| Fuel oil and diesel | 3125 | 17,993 | 8025 | 49,842 |
| Nuclear | 2000 | 14,000 | 10,000 | 70,000 |
| Hydro and renewables | 24,982 | 85,719 | 30,031 | 104,043 |
| Total | 65,069 | 347,294 | 109,218 | 623,768 |

Source: [2].

Table 2
Installed photovoltaic systems in Turkey

| Institution | Purpose | Location | Installed power (kWp) |
|---|---|---|---|
| The General Directorate of Electrical Power Resources Survey and Development Administration (EIE) | Photovoltaic lighting units | Ankara | 0.2 |
| | | Didim (Research and Training Center) | 0.2 |
| | | Ankara (EIE building) | 0.1 |
| | | Didim | 0.16 |
| | Photovoltaic area lighting | Didim (Research and Training Center) | 1.0 |
| | Photovoltaic water pumping systems | – | 0.616 |
| | | EIE Renewable Energy Park | 0.756 |
| | Photovoltaic traffic warning system | | 0.050 |
| | Grid-connected | Didim (Research and Training Center) | 4.8 |
| | | EIE Renewable Energy Park | 1.2 |
| | | EIE total | 9.082 |
| Turkish Telecom | Telecommunication stations | Various | 75 |
| The Ministry of Forestry | Observation towers | Various | 151 |
| The General Directorate of the Maritime Enterprise | Beacons | Various | 3.5 |
| Turkcell Telecom | Telecommunication stations | Various | 6.7 |
| Mugla University | Photovoltaic-house | Mugla | 25.0 |
| Hacettepe University | Photovoltaic-house | Ankara | 1.0 |
| Mustafa Kemal University | Test rig | Hatay | 0.24 |
| Overall total | | | 271.52 |

## 2. Photovoltaic system applications

The cumulative sale of photovoltaic modules has increased from 500 MW in 1994 [5] to 1000 MW as of the year 2000 [6]. Photovoltaics have been the fastest growing energy technology in the world from 1995 to 2000, with the average growth rate of 29% over this

Table 3
Annual average solar energy potential by regions of Turkey

| | Solar radiation (kWh/m$^2$) | Sunshine duration (h) |
|---|---|---|
| Marmara | 1168 | 2409 |
| Southeast Anatolia | 1460 | 2993 |
| Aegean | 1304 | 2738 |
| Mediterranean | 1390 | 2956 |
| Black Sea | 1120 | 1971 |
| Central Anatolia | 1314 | 2628 |
| East Anatolia | 1365 | 2664 |
| Average | 1303 | 2623 |

Source: [4].

period [7]. The countries with most installed photovoltaic power currently are Germany, Japan, Italy and the USA, which are being the biggest photovoltaic module producing countries as well. The 90% of the whole photovoltaic modules produced in the world are produced in the USA, Japan and the European Union (EU) countries. The EU countries have set a target of 3000 MW of installed photovoltaic power by the year 2010. The increase in the production rate of photovoltaic modules has been 15% annually in the last decade. Most of these photovoltaic modules were used in stand-alone applications in places where the grid-connection was non-existent [8]. As a result of the high growth rate of stand-alone photovoltaic applications throughout the world, many articles have been published to calculate their performance [9–16]. As well as the stand-alone photovoltaic systems, researchers studied the performance of hybrid photovoltaic systems [17–21].

The grid-connected photovoltaic systems have experienced a rapid growth in recent years. The fastest growing segment has been the grid-connected photovoltaic, which rose to 48% of all photovoltaic sales in 2000, up from just 4% in 1990 [7]. This was achieved mostly through the government-induced energy policies of especially the developed countries, pioneered by Germany and Switzerland in early 1990s [22]. The first comprehensive international dissemination programme was the ‘1000 roofs program’ launched in Germany in 1990. The plant installations were completed in 1995, with some 2250 roofs equipped with photovoltaic systems of an average size of 2.6 kWp [23]. In Japan, the first residential photovoltaic power generating system connected to utility line started its operation in 1992, consisting of a 1.8 kWp photovoltaic array and a 3 kVA inverter [24]. This paved the way for the largest dissemination program implemented in the world so far, which was launched in Japan in 1994 [25]. Within this programme, more than 58.000 small grid-connected systems, have been installed until 2001 in Japan, adding up to a total of 331.7 MWp. Between 1992 and 1994 a 200 kWp-rooftop programme to promote small grid-connected photovoltaic systems was conducted in Austria [26]. The key factors for a further dissemination of photovoltaic systems derived from this programme are summed up in the same article as: financial incentives, a reduction of the investment costs, increase in reliability, distribution of information and enhancement of environmental awareness. Nowadays, more and more articles appear in the literature reporting on the grid-connected photovoltaic systems, such as those from Poland [27], Spain [28], and Croatia [29].

One of the most comprehensive programs on the grid-connected photovoltaic systems was undertaken by the Photovoltaic Power Systems Programme (PVPS), which is one of the collaborative research and development agreements established within the International Energy Agency (IEA). The PVPS has 20 countries as member including Turkey. A report was prepared by Rezzonico and Nowak [30] under the supervision of PVPS Task I. In this report, the commitment of the member countries to promote photovoltaic power systems is analysed. The most important single parameter as the measure of the commitment of governments to promote and propagate the grid-connected photovoltaic systems into their conventional energy generation systems is defined as the ‘buy-back ratio’ ($r$), which is the ratio between the payment of the photovoltaic energy inserted into the grid ($Cpv_{in}$) and the cost of conventional energy taken from the grid ($C_{out}$), i.e. $r = Cpv_{in}/C_{out}$. The main objective of the report was to study and catalogue different buy-back rate models in the member countries. However, only eleven of

Table 4
Countries classified by 'importance' of photovoltaic energy compared to conventional energy

| 'Importance' of photo-voltaic energy | Buy-back ratio, $r$ | Country |
|---|---|---|
| | ≅5…6 | Germany, Switzerland |
| Very important | ≅1…2 | Italy |
| ⇓ | ≅1 | Japan, Netherlands (CHE and AUS in some cases) |
| ⇓ | ≅0.8 | Austria, Germany (by law) |
| ⇓ | ≅0.5…0.7 | Australia, Portugal, Spain (NLD in some cases) |
| Not important | ≅0.3…0.4 | France and United Kingdom |
| | ≅0 or no models | Korea, Sweden, Denmark, Canada |

Source: [30]

the member countries considered or implemented a photovoltaic program and therefore had experience with buy-back rate models. These countries are shown in Table 4 with the buy-back ratios they used. Even though a member of the PVPS, Turkey is not amongst these eleven countries, as she has not had a photovoltaic program in progress or considered implementing a new one.

## 3. Analysis of weather data used

For Ankara, the climate data for the calendar year of 2000 are taken as the typical weather year. The solar radiation data, collected by the Turkish State Meteorological Service, measured on horizontal plane on an hourly basis, are given as monthly averages on the second column of Table 5. The data measured on horizontal plane were converted to that on a tilted plane that is equal to the latitude of Ankara (40.0°N). The solar radiation calculated on the tilted surface is given as monthly averages on the third column of

Table 5
Solar radiation statistics for the calendar year of 2000 in Ankara

| Months | On horizontal ($kWh/m^2$) | On a tilted plane ($kWh/m^2$) | Extraterrestrial ($kWh/m^2$) | Clearness index |
|---|---|---|---|---|
| January | 55.59 | 83.37 | 131.43 | 0.42 |
| February | 78.33 | 109.10 | 164.59 | 0.48 |
| March | 137.69 | 170.12 | 239.04 | 0.58 |
| April | 129.51 | 134.40 | 290.26 | 0.45 |
| May | 187.35 | 182.22 | 342.89 | 0.55 |
| June | 189.56 | 178.09 | 346.76 | 0.55 |
| July | 221.05 | 212.09 | 348.11 | 0.64 |
| August | 189.28 | 195.53 | 310.55 | 0.61 |
| September | 151.39 | 178.56 | 245.27 | 0.62 |
| October | 106.16 | 147.89 | 188.67 | 0.56 |
| November | 70.12 | 107.80 | 134.27 | 0.52 |
| December | 50.27 | 72.49 | 116.89 | 0.43 |
| Monthly average | 130.52 | 147.64 | 238.23 | 0.53 |
| The worst month | 50.27 | 72.49 | 116.89 | 0.42 |

the same table, as well as the extraterrestrial radiation on the forth column. The monthly clearness indices are given in the last column of the table.

## 4. The photovoltaic cell model

The basic model for a photovoltaic module is shown in Fig. 1. The non-linear nature of the photovoltaic power is due to the radiation level and the ambient and module temperatures. The current–voltage ($I$–$V$) characteristic of the photovoltaic modules can be described as

$$I = I_\mathrm{L} - I_\mathrm{o}\left[\exp\left(\frac{V + IR_\mathrm{s}}{V_\mathrm{t}}\right) - 1\right] - \frac{V + IR_\mathrm{s}}{R_\mathrm{sh}} \tag{1}$$

where $I_\mathrm{L}$ is the light generated current (A), $I_\mathrm{o}$ is the reverse saturation current of the p–n diodes (A), $R_\mathrm{s}$ is the series resistance of the cells (Ohms), $R_\mathrm{sh}$ is the shunt resistance of the cells (Ohms) and $V_\mathrm{t}$ is the thermal voltage depending on the cell temperature, defined as

$$V_\mathrm{t} = kT_\mathrm{c}/q \tag{2}$$

In Eq. (2), $T_\mathrm{c}$ is the cell temperature (K) and $k$ and $q$ are constants. The short circuit current can be found when $V=0$, i.e. $I_\mathrm{sc}=I_\mathrm{L}$. $R_\mathrm{sh}$ is usually ignored, as it is very large for mono-crystalline cells as compared to $R_\mathrm{s}$, Eq. (2) is then reduced to

$$I = I_\mathrm{L} - I_\mathrm{o}\left[\exp\left(\frac{V + IR_\mathrm{s}}{V_\mathrm{t}}\right) - 1\right] \tag{3}$$

The simple relationship of power for a photovoltaic module is

$$P = IV \tag{4}$$

Introducing Eq. (3) into Eq. (4), the power would be

$$P = IV = \left\{I_\mathrm{L} - I_\mathrm{o}\left[\exp\left(\frac{V + IR_\mathrm{s}}{V_\mathrm{t}}\right) - 1\right]\right\}V \tag{5}$$

A method is summarised by Kou et al. [31] to identify the four parameters required to calculate the power output. The maximum power output is, provided that a maximum

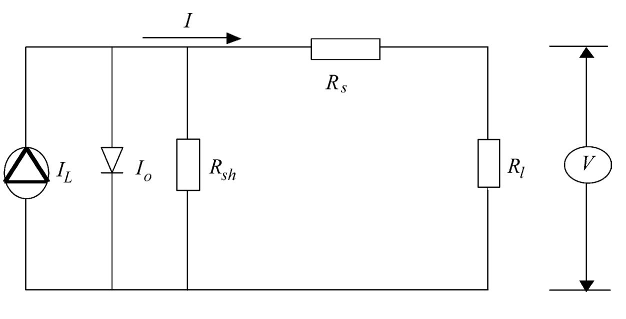


Fig. 1. The basic model for a photovoltaic module.

power point tracker (MPPT) is used in the system,

$$P_{max} = I_{mp} V_{mp} \tag{6}$$

where $V_{mp}$ and $I_{mp}$ are the voltage and current at maximum power points. The maximum power points occur when $\partial P/\partial V = 0$. Differentiating power with respect to $V$ and setting the derivative equal to zero yields the following,

$$\exp\left(\frac{V_{mp} + I_{mp} R_s}{V_t}\right)\left(1 + \frac{V_{mp}}{V_t}\right) - \frac{I_L}{I_o} - 1 = 0 \tag{7}$$

Introducing this into Eq. (3), the current at the maximum power point is obtained as,

$$I_{mp} = (I_L + I_o)\left[1 - \frac{V_t}{(V_t + V_{mp})}\right] \tag{8}$$

Finally the maximum power and the corresponding cell efficiency are given by,

$$P_{max} = I_{mp} V_{mp} = (I_L + I_o)\left[1 - \frac{V_t}{(V_t + V_{mp})}\right] V_{mp} \tag{9}$$

$$\eta_{max} = \frac{P_{max}}{G \times A} \times 100\% \tag{10}$$

## 5. The battery simulation algorithm

There is a variety of models developed to simulate the battery behaviour used in photovoltaic energy systems. The models vary from simple sate of charge-based (SoC) [18] to more complex state of voltage-based (SoV) [32] models. It is unanimously agreed that over and under voltage control strategies are required to prevent the battery from excessive charge and discharge, thus making sure a prolonged battery life [33]. This is essential for the whole photovoltaic energy system to ensure a high reliability required in such remote and autonomous applications. Prolonged battery life will also eventually lead to a reduction in the cost of the system, thus reduction in the cost of electricity produced in the system. The battery algorithm developed in [32] is used in the present article. The net battery operational current at any time of operation is

$$I = I_{PV} - I_L \tag{11}$$

where $I_{PV}$ is the input current from the photovoltaic generator and $I_L$ is the current corresponding to the load demand. The battery voltage $V_b$ is given by,

$$V_b = V_o + K_e \ln\left[1 - \frac{Q}{C(I)}\right] + R_{tot} I \tag{12}$$

where $V_o$ is a constant and represents the battery voltage at the start of the time step, $R_{tot}$ is the total internal resistance and assumed to be a constant term, $Q$ is the exchanged charge for one time step, $C(I)$ is the battery capacity as a function of the current, and $K_e$ is a battery model coefficient. The exchanged charge, $Q$, from the time point $t_n$ to the time point $t_{n+1}$ is

given by the integral

$$Q = \int_{t_n}^{t_{n+1}} |I| \mathrm{d}t = |I| \Delta t \tag{13}$$

The relationship between the charge/discharge rate $I$ and the battery capacity $C$, involves three capacity coefficients, i.e. $C_1$, $C_2$ and $C_3$,

$$C(I) = \frac{C_1}{C_2 |I|^{C^3} + 1} \tag{14}$$

Differentiating Eq. (12) with respect to time, Eq. (15) is obtained.

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \frac{K_e}{C(I) - Q}\left[I + \frac{C(I)C_2C_3QIC_3 - 1}{C_1}\frac{\mathrm{d}I}{\mathrm{d}t}\right] + R_{\mathrm{tot}}\frac{\mathrm{d}I}{\mathrm{d}t} \tag{15}$$

For the steady state operation setting $\mathrm{d}I/\mathrm{d}t = 0$,

$$\frac{\mathrm{d}V}{\mathrm{d}t} = K_e\left[\frac{I}{C(I) - Q}\right] \tag{16}$$

The battery voltage at a time $n+1$ can be calculated using the battery voltage at an earlier time period of $n$,

$$V_{\mathrm{b},n+1} = V_{\mathrm{b},n} + \frac{\mathrm{d}V}{\mathrm{d}t}\Delta t \tag{17}$$

The dynamic battery operation is characterised by a sudden change in the value of the current. This sudden change is simulated by introducing a very small time step, $e$. No charge $Q$ will be exchanged between time levels $n$ and $n+e$. Because photovoltaic systems work under variable operation most of the time due to the changing photovoltaic solar irradiance, it is the battery's total internal resistance, $R_{\mathrm{tot}}$, which governs the battery's voltage behaviour as follows

$$\Delta V = V_{n+e} - V_n = \Delta I R_{\mathrm{tot}} \tag{18}$$

## 6. Life cycle cost analysis

The following cost analysis model is adopted in the present article in which the life cycle cost is calculated as follows

$$\mathrm{LCC} = C + M + R - S \tag{19}$$

where $C$ is the capital cost, $M$ is the operation and maintenance cost, $R$ is the repair and replacement cost and $S$ is the salvage value. In this cost analysis model, all the costs are converted to present worth value as follows for the single present value and for the uniform present value, respectively

$$P = \frac{F}{(1+I)^N} \tag{20}$$

$$P = \frac{A[1-(1+I)^{-N}]}{I} \tag{21}$$

where $F$ and $A$ are a sum of money (capital equipment), $N$ is a given year for Eq. (20) and is the period of time in question for Eq. (21) and $I$ is the net discount rate (i.e. nominal discount rate minus the rate of inflation). The present worth factor for a single payment is $P/F$, and, for an annual payment, $P/A$.

Technical specifications and the capital costs of the components and parameters used in life cycle cost analysis are respectively, given in Tables 6 and 7. The capital costs of the components are the retail prices taken from a firm working in the photovoltaic field in Turkey. The prices include the VAT rate of 18% as applied in other goods in the country. A comparison made by the author of this article showed that the photovoltaic module price on average is some 40% more expensive in Turkey than it is in Europe. The life cycle cost analysis of the systems designed according to two different sizing approaches, which will be explained in detail in Section 7, is presented in Table 8.

## 7. Techno-economic analysis

The weekly load profile used in the present article is given in Fig. 2. The daily electricity consumption is assumed 9.4 kWh on average. Therefore, the monthly total energy demand varies between 273 and 290 kWh throughout the year. The energy produced by a single photovoltaic panel is calculated using the hourly measured time-series solar radiation data on a tilt angle of 40° using the theory given above. The number of photovoltaic panels to be used to meet the load is calculated for each month. Then,

Table 6
Technical specifications of the components

| Photovoltaic module | | Inverter | | Battery | |
|---|---|---|---|---|---|
| Manufacturer | GT Solar | Manufacturer | PowerMaster | Manufacturer | Mutlu Akü |
| Model | OST-74 | Model | PM-3000 | Model | 12 V/150 A |
| Nominal power (W) | 74 | Continuous power output | 3000 W | | |
| Voltage (V) | 17 | Instant load | 9000 W | Capacity (Ah) | 150 |
| Current (A) | 4.35 | AC output voltage | 230 V | Capacity (kWh) | 18.8 |
| Open circuit voltage (V) | 21.81 | DC input voltage | 10–16 V | Voltage (V) | 12.0 |
| Short circuit current (A) | 4.8 | Battery cut-off voltage alarm | 10.0 V | Low voltage disconnect (V) | 10.8 |
| Mass (kg) | 7.5 | Battery cut-off voltage | 9.8 V | Low voltage re-connect (V) | 11.0 |
| Length (cm) | 121 | Frequency | 50 Hz +/− 1% | High voltage disconnect (V) | 14.0 |
| Width (cm) | 55 | Efficiency | 95–98% | High voltage re-connect (V) | 13.8 |

Source: Orjin Solar Ltd, http://www.orjinsolar.com.tr.

Table 7
Capital cost of the components and parameters used in life cycle cost analysis

| Component | Price ($) | Sizing approach 1 | | Sizing approach 2 | |
|---|---|---|---|---|---|
| | | Number used | Replace-ment | Number used | Replace-ment |
| Photovoltaic | 556.0 | 27 | 1 | 41 | 1 |
| Battery | 227.0 | 11 | 4 | 11 | 5 |
| Controller (144 W) | 112.0 | 6 | 1 | – | 1 |
| Controller (192 W) | 140.0 | 5 | 1 | 3 | 1 |
| Controller (244 W) | 200.0 | – | 1 | 8 | 1 |
| Inverter | 940.0 | 1 | 1 | 1 | 1 |
| MPPT | 250.0 | 6 | 1 | 8 | 1 |
| Array installation cost ($/$W_p$) | \$0.6/$W_p$ | | | | |
| Array life | 25 years | | | | |
| Battery life | 7 years | | | | |
| Controller and inverter life | 13 years | | | | |
| Annual operation and mainten-ance cost | 1% of initial capital cost | | | | |
| Net discount rate | 5% | | | | |

the system is sized using two different approaches. In the first approach, the system is sized such that the ratio of energy production to energy demand is equal to unity on a yearly basis. In the second approach, the system is sized such that the energy production to energy demand is equal to unity in the worst month. The worst month is that the most amount of photovoltaic module is required to meet the load demand. The number of photovoltaic modules required for these approaches is given in Table 9. The monthly and yearly total energy production and the ratio of energy production to energy demand ($R_{P/L}$) are presented in Table 10 for the systems with and without battery storage. The performance of photovoltaic systems may be quantified by one of the terms 'loss of load probability', 'deficit of energy', or 'loss of power probability'. Over a time period of $t$, loss of load probability (LLP) is given by,

$$\mathrm{LLP} = \frac{\int_0^t \text{Energy deficit}}{\int_0^t \text{Energy demand}} \tag{22}$$

Alternatively, the photovoltaic system performance can be defined by the terms 'autonomy', 'load coverage rate', or 'solar fraction'. The relation between LLP and autonomy (A) is

$$\mathrm{A} = 1 - \mathrm{LLP} \tag{23}$$

Even though the terms defining the performance of photovoltaic systems were usually used for stand-alone systems, such terms are also required to quantify the reliability in grid-connected photovoltaic systems. This is necessary to carry out a thorough techno-economic analysis of grid-connected photovoltaic systems. The grid-connected photovoltaic system performance is given in terms of autonomy in the present article. For example, an autonomy value of 0.53 means that 53% of the load demand is met by

Table 8
Life cycle cost analysis of the systems designed according to different sizing approaches

| | Sizing approach 1 | | | | | Sizing approach 2 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Single present worth year | Uniform present worth year | Cost ($) | Present worth factor | Present worth ($) | Single present worth year | Uniform present worth year | Cost ($) | Present worth factor | Present worth ($) |
| *1. Capital equipment* | | | | | | | | | | |
| Photovoltaic | – | – | 15,012 | 1.00 | 15,012 | – | – | 22,796 | 1.00 | 22,796 |
| Battery | – | – | 2497 | 1.00 | 2497 | – | – | 2497 | 1.00 | 2497 |
| Controller (144 W) | – | – | 672 | 1.00 | 672 | – | – | 0 | 1.00 | 0 |
| Controller (192 W) | – | – | 700 | 1.00 | 700 | – | – | 420 | 1.00 | 420 |
| Controller (244 W) | – | – | 0 | 1.00 | 0 | – | – | 1600 | 1.00 | 1600 |
| Inverter | – | – | 940 | 1.00 | 940 | – | – | 940 | 1.00 | 940 |
| MPPT | – | – | 1500 | 1.00 | 1500 | – | – | 2000 | 1.00 | 2000 |
| Other components | – | – | 1000 | 1.00 | 1000 | – | – | 1000 | 1.00 | 1000 |
| Installation | – | – | 1199 | 1.00 | 1199 | – | – | 1820 | 1.00 | 1820 |
| Sub-total | | | | | 23,520 | | | | | 33,073 |
| *2. Operation and maintenance* | | | | | | | | | | |
| Labour: yearly inspection | | 25 | 220 | 14.09 | 3315 | – | 25 | 311 | 14.09 | 4661 |
| *3. Repair and replacement* | | | | | | | | | | |
| Battery | 7 | – | 2497 | 0.71 | 1775 | 7 | – | 2497 | 0.71 | 1775 |
| Battery | 14 | – | 2497 | 0.51 | 1261 | 14 | – | 2497 | 0.51 | 1261 |
| Battery | 21 | – | 2497 | 0.36 | 896 | 21 | – | 2497 | 0.36 | 896 |
| *4. Salvage* | | | | | | | | | | |
| 20% of original cost of equipment | 25 | | 4404 | 0.30 | 1389 | 25 | | 6215 | 0.30 | 1953 |
| Total | | | | | 29,378 | | | | | 39,713 |

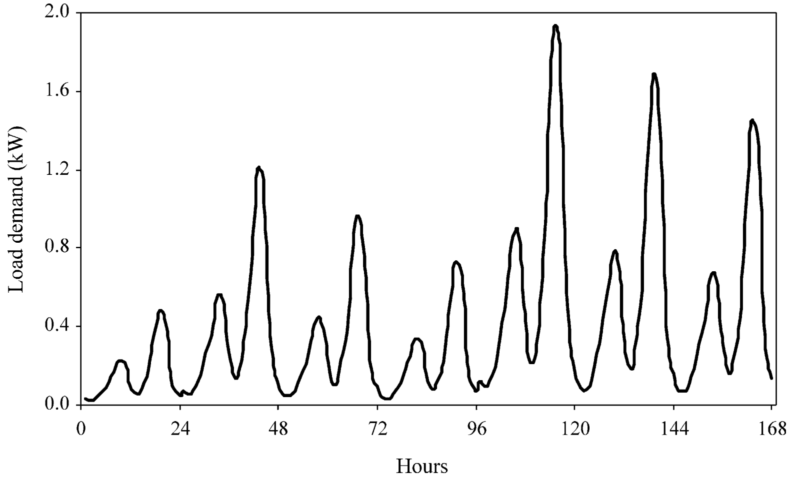


Fig. 2. Weekly load profile used in the present study.

the photovoltaic system. The energy deficit of 47% in the case of a grid-connected photovoltaic system may be provided from the grid. The level of autonomy is always smaller than the ratio of energy production to energy demand due to the mismatch of production and load demand in time. Then, the excess energy may be fed to the grid. Monthly autonomy values are calculated via a computer program coded in FORTRAN language. The theory presented above is coded in the program, including the appropriate battery control algorithms. The system performance is simulated using the hourly time-series solar radiation and ambient temperature data. The monthly and yearly average

Table 9
The number of photovoltaic modules required according to different sizing approaches

| Months | Solar radiation (kWh/m$^2$) | Energy production per photovoltaic module (kWh) | Load demand (kWh) | Number of photovoltaic module |
|---|---|---|---|---|
| January | 109.76 | 7.33 | 290.64 | 39.67 |
| February | 130.03 | 8.63 | 273.28 | 31.66 |
| March | 182.72 | 12.10 | 290.64 | 24.02 |
| April | 142.43 | 9.51 | 282.95 | 29.76 |
| May | 181.98 | 12.14 | 290.64 | 23.94 |
| June | 175.61 | 11.73 | 282.83 | 24.10 |
| July | 211.16 | 14.10 | 290.64 | 20.62 |
| August | 199.68 | 13.31 | 290.64 | 21.83 |
| September | 189.74 | 12.64 | 282.83 | 22.38 |
| October | 167.02 | 11.14 | 290.64 | 26.10 |
| November | 132.61 | 8.88 | 283.00 | 31.86 |
| December | 104.98 | 7.05 | 290.55 | 41.19 |
| Sizing approach 1 | 160.64 | 10.71 | 286.61 | 286.61/10.71 = 26.76 |
| Sizing approach 2 | 104.98 | 7.05 | 290.55 | 290.55/7.05 = 41.19 |

Table 10
Monthly and yearly total energy production and the ratio of energy production to energy demand ($R_{P/L}$) according to different sizing approaches

| Months | Energy production (kWh) | | Load demand (kWh) | $R_{P/L}$ | | With battery storage | | Without battery storage | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Autonomy | | Autonomy | |
| | Approach 1 | Approach 2 | | Approach 1 | Approach 2 | Approach 1 | Approach 2 | Approach 1 | Approach 2 |
| January | 197.82 | 300.40 | 290.64 | 0.68 | 1.03 | 0.53 | 0.79 | 0.26 | 0.30 |
| February | 233.05 | 353.89 | 273.28 | 0.85 | 1.29 | 0.66 | 0.89 | 0.31 | 0.33 |
| March | 326.76 | 496.19 | 290.64 | 1.12 | 1.71 | 0.87 | 0.96 | 0.36 | 0.38 |
| April | 256.69 | 389.79 | 282.95 | 0.91 | 1.38 | 0.72 | 0.92 | 0.35 | 0.37 |
| May | 327.80 | 497.77 | 290.64 | 1.13 | 1.71 | 0.86 | 0.98 | 0.38 | 0.40 |
| June | 316.84 | 481.13 | 282.83 | 1.12 | 1.70 | 0.86 | 0.97 | 0.41 | 0.45 |
| July | 380.58 | 577.92 | 290.64 | 1.31 | 1.99 | 0.98 | 1.00 | 0.45 | 0.49 |
| August | 359.48 | 545.88 | 290.64 | 1.24 | 1.88 | 0.96 | 1.00 | 0.41 | 0.44 |
| September | 341.21 | 518.14 | 282.83 | 1.21 | 1.83 | 0.93 | 0.99 | 0.38 | 0.40 |
| October | 300.69 | 456.60 | 290.64 | 1.03 | 1.57 | 0.79 | 0.96 | 0.35 | 0.38 |
| November | 239.80 | 364.14 | 283.00 | 0.85 | 1.29 | 0.66 | 0.93 | 0.29 | 0.32 |
| December | 190.46 | 289.22 | 290.55 | 0.66 | 1.00 | 0.51 | 0.76 | 0.28 | 0.31 |
| Average | 289.27 | 439.26 | 286.61 | 1.01 | 1.53 | 0.78 | 0.93 | 0.35 | 0.38 |
| Total | 3471.19 | 5271.07 | 3439.30 | | | | | | |

autonomy values obtained from the simulations are presented in Table 10 for different system layouts, namely with and without battery storage.

The parameters for the techno-economic analysis of the grid-connected photovoltaic-house for Ankara are given in Table 11 for the two sizing approaches, with and without battery storage options. It is seen that with battery storage the monthly autonomies are significantly larger, more than twice, than those without battery storage for both of the sizing approaches. Even though the life time cost is smaller for the systems without storage battery, the cost of electricity per kWh is considerably larger when compared to the systems with battery storage. This is because the energy spent on the load is excessively small. The excess energy will have to be dumped if it cannot be sold to the grid. Therefore, the systems without battery storage are not an ideal option when selling the excess energy to the grid company is not an option. The cost of grid electricity is over 0.13 $/kWh in Turkey (as of February 2004) and it is likely that it will rise gradually in the near future. Therefore, the electricity is some 3 times expensive by a photovoltaic system with battery storage sized by the first approach while it is 5 times expensive for systems without battery

Table 11
Techno-economic analysis of the grid-connected photovoltaic system

| | With battery storage | | | | Without battery storage | | | |
|---|---|---|---|---|---|---|---|---|
| | Sizing approach 1 | | Sizing approach 2 | | Sizing approach 1 | | Sizing approach 2 | |
| Yearly autonomy | 0.78 | | 0.93 | | 0.35 | | 0.38 | |
| Energy demand (kWh) | 85982.45 | | 85982.45 | | 85982.45 | | 85982.45 | |
| Energy produced (kWh) | 86665.27 | | 131602.82 | | 86665.27 | | 131602.82 | |
| Energy spent on the load (kWh) | 66801.20 | | 79798.88 | | 30129.68 | | 32587.35 | |
| Excess energy (kWh) | 19864.07 | | 51803.94 | | 56535.59 | | 99015.47 | |
| Energy deficit (kWh) | 19181.25 | | 6183.57 | | 55852.77 | | 53395.10 | |
| Peak power (kW@ 1 kW/m$^2$, 25 °C) | 2.0 | | 3.0 | | 2.0 | | 3.0 | |
| Life time cost ($) | 29,378 | | 39,713 | | 21,260 | | 30,895 | |
| Installed cost ($/Wp) | 14.70 | | 13.09 | | 10.64 | | 10.18 | |
| Cost of photovoltaic el. ($/kWh) | 0.44 | | 0.50 | | 0.71 | | 0.95 | |
| Buy-back ratio, *r* | Life time cost ($) | Electricity cost ($/kWh) | Life time cost ($) | Electricity cost ($/kWh) | Life time cost ($) | Electricity cost ($/kWh) | Life time cost ($) | Electricity cost ($/kWh) |
| 1 | 29288.81 | 0.34 | 33782.77 | 0.39 | 21171.02 | 0.25 | 24963.91 | 0.29 |
| 2 | 26706.48 | 0.31 | 27048.26 | 0.31 | 13821.39 | 0.16 | 12091.90 | 0.14 |
| 3 | 24124.16 | 0.28 | 20313.75 | 0.24 | 6471.77 | 0.08 | −780.12 | −0.01 |
| 4 | 21541.83 | 0.25 | 13579.23 | 0.16 | −877.86 | −0.01 | −13652.13 | −0.16 |
| 5 | 18959.50 | 0.22 | 6844.72 | 0.08 | −8227.49 | −0.10 | −26524.15 | −0.31 |

storage. As seen from the same table, the life time system cost and the cost of electricity per kWh figures change considerably when it is possible to sell the excess electricity to the grid company. The costs are then greatly depended on the buy-back ratio applied. For the system without battery storage, the excess energy is excessively large. If the excess energy can be sold to the grid, both the life time system costs and the cost of electricity per kWh fall sharply when compared to the case where selling back to the grid was not possible. However, this is on the supposition that the grid-electricity company would agree to buy all the excess energy. If the amount of electricity that is bought back by the grid company is limited, both of the costs are bound to change. Alternative to limiting the amount of back-buyable electricity, the grid company may stipulate that a minimum autonomy level (for example 0.8) is required from a grid-connected photovoltaic-house. The buy-back ratios larger than one do not seem likely to be implemented in Turkey. This is especially so for the systems without battery storage since such systems with a buy-back ratio of 3 and higher turn out to be a profitable investment. However, for the photovoltaic systems with battery storage, the cost of electricity per kWh comes to an affordable level for the people when compared to 0.13 $/kWh of grid electricity. It should however be remembered that if subsidised and exempted from the taxes, the total cost and the cost of electricity per kWh might be brought to a much comparable level to that of the grid electricity price. The governments in Turkey therefore should take the necessary steps to reduce and bring this excessive cost of photovoltaic modules to the level of Europe. Besides, further subsidies are necessary to propagate the alternative energy systems.

## 8. Conclusions

In the present article, the current status of photovoltaic energy in Turkey was studied and the lifetime techno-economic analysis of a grid-connected photovoltaic system was carried out for Ankara, the capital city of Turkey. The most important conclusions arising from the present study can be summarised as follows:

1. The current installed photovoltaic energy capacity of approximately 300 kW in Turkey is insignificant when compared to the economically utilizable solar energy potential.
2. Even though Turkey is a member of the IEA, she did not take part in any of the photovoltaic energy programs initiated by the IEA. However, the developed countries took part in the IEA project, as well as their own photovoltaic programs.
3. The rate of primary energy production to consumption in Turkey has been significantly decreasing recently in Turkey. The alternative and renewable energy systems in general and photovoltaics in particular should be included in the new energy programs in Turkey.
4. It was shown that the photovoltaic system components, photovoltaic modules primarily, are on average 40% more expensive in Turkey than those in Europe.
5. The theoretically designed grid-connected photovoltaic-house in Ankara revealed that the cost of electricity per kWh is 3–4 times more expensive than the grid electricity, with battery storage systems, without a buy-back ratio. This ratio increases considerably for the systems without storage battery. With a buy-back option,

the electricity cost comes to a reasonable level for the photovoltaic systems with battery storage.
6. Even though the cost of electricity per kWh is on par with the grid electricity or cheaper for no-battery storage systems for the higher buy-back ratios, such high buy-back ratios seem unlikely to be applied in Turkey.
7. The photovoltaic system components and the cost of photovoltaic electricity per kWh can be significantly reduced if they are exempted of the taxes and furthermore the governments introduce subsidies.

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